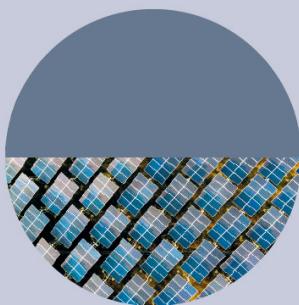


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The use of ash-mineral mixtures for the construction of high-strength coatings of forest roads

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Abstract. Forest roads are characterized by difficult transport and operating conditions and a considerable distance from sources of traditional road-building materials. Local ash and slag waste of the state district power station is an effective road-building material for the construction of forest roads. The article presents the test results of the building properties of the ash of the Reftinskaya TPP and the physicommechanical characteristics of the ash-mineral mixtures prepared with its use. Based on the results of laboratory studies, technical solutions for the use of ash-mineral mixtures in the design and construction of high-strength coatings of forest roads have been developed: the main design indicators, requirements for the materials used in the composition, approximate compositions of the ash-mineral mixtures are given, technical measures for the organization and quality control of construction work are assigned.

1. Introduction

The construction of an extensive network of long-lasting forest roads with a minimum cost is an important industry task, which allows for reliable, stable and year-round transportation of wood. Therefore, it is relevant to search for effective road-building materials that allow building quality roads in the forest zone. The use of secondary resources - industrial wastes as materials for road construction is one of the main tasks of the state program for the processing of technogenic materials and their involvement in economic turnover. At the same time, the tasks of the integrated use and disposal of industrial wastes, improving the environmental situation at industrial enterprises and the territories adjacent to them are solved.

One of these wastes is ash and slag - products of the burning of solid fuels - coal, peat, shale, and combustible materials at thermal power plants. Scientific research and construction practice have shown that ash and slag from burning solid fuels are materials suitable for use in many sectors of the economy, including road construction [1].

The main areas of forest raw material bases are usually significantly removed from the sources of traditional road-building materials: crushed stone materials and crushed stone-sand mixtures. At the same time, the difficult operating conditions of forest roads, characterized by the impact of heavy road transport and weak local soils, require the use of strong and durable road-building materials. Therefore, the use of local ash and slag waste from the state district power station is an effective road-building material for the construction of forest roads [2].

To confirm this hypothesis, laboratory studies were conducted. The purpose of the laboratory studies was to study the construction properties from the state district power station ash, using the Reftinskaya state district power station ash located in the Sverdlovsk region of the Russian Federation



as an example for further development of technical solutions for its use as a part of ash-mineral mixtures for the construction of high-strength coatings of forest roads.

1.1. Research tasks

- Study of the chemical and phase-mineralogical composition of the ash at Reftinskaya state district power station.
 - Investigation of the particle size distribution of the ash at Reftinskaya state district power station.
 - Investigation of the physico-mechanical and physico-chemical properties of the ash of Reftinskaya state district power station.
 - Analysis of the results of studies of the construction properties of ash and the development of technical solutions for the use of ash at Reftinskaya state district power station as a part of ash-mineral mixtures for the construction of high-strength coatings of forest roads.

2. Methods and Materials

For laboratory research, ash samples were taken at the ash dump of Reftinskaya state district power station. Ash tests were carried out on the basis of relevant regulatory documents. Types of tests and regulatory documents are presented in table 1.

Table 1. Types of tests and regulatory documents.

Name of soil characteristics	Regulatory document
Soils. Laboratory methods for the determination of particle size (grain) and microaggregate composition.	GOST 12536 [3]
Building materials and products. Method for determination of thermal conductivity and thermal resistance under stationary thermal conditions.	GOST 5180 [4]
Soils. Laboratory methods for characterizing strength and deformability.	GOST 12248 [5]
Soils. Laboratory methods for determining the maximum density.	GOST 22733 [6]

3. Results and Discussion

3.1. The results of studies of the construction properties of ash Reftinskaya state district power station

Under the construction properties of ash are understood its physical, physico-chemical, water and physico-mechanical properties, manifested under the influence of natural and mechanical influences during the construction and operation of roads.

The chemical composition of the ash is presented in table 2. It varies within certain limits and mainly depends on changes in the chemical composition of the inorganic component of coal supplied for the needs of Reftinskaya state district power station.

Table 2. The chemical composition of the ash Reftinskaya state district power station.

Type of material	Chemical composition, % by weight										
	Al ₂ O ₃	SiO ₂	CaO	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	SO ₃	TiO ₂	P ₂ O ₅	LOI
Ash Reftinskaya state district power station:											
- possible changes in the content of oxides;	23.0-40.2	53.0-61.0	1.1-1.7	3.2-4.5	0.62-1.00	≤0.60	≤0.25	0.64-0.70	≤1.38	0.28-0.63	1.00-3.25
- weighted average values	31.56	56.92	1.40	3.84	0.81	0.60	0.25	0.67	1.38	0.45	2.12

An analysis of the chemical composition of the ash at Reftinskaya state district power station indicates that this material is acidic and has a very low potential for the manifestation of hydraulic properties. The phase-mineralogical composition indicates that ash is represented by stable compounds and minerals that are not susceptible to various types of decomposition under the influence of weather and climate factors and mechanical stresses. Ash is not aggressive to building structures based on cement, bitumen, etc. To metal structures, ash is moderately aggressive.

The results of determining the granulometric (grain) composition of the ash are presented in table 3. The grain size composition of the ash at Reftinskaya state district power station is similar to dusty sands according to GOST 25100 [7].

Table 3. Granulometric composition of ash Reftinskaya state district power station.

Granulometric composition, % (partial residues on sieves)								
Total >2 mm	Sand fractions, mm				Total sand fractions	Dust fractions, mm		Clay fractions, mm
	2-0.5	0.5- 0.25	0.25- 0.1	0.1-0.05		0.05- 0.01	0.01- 0.005	
0.0	0.1	3.6	16.5	16.8	37.0	53.8	6.0	3.2
0.0	0.1	4.0	16.1	18.8	39.0	50.2	8.0	2.8

The results of studies of the maximum skeleton density ρ_{\max} and optimal ash moisture W_{opt} show that the ash of the Reftinskaya state district power station does not have clearly expressed optimal humidity and maximum skeleton density. Based on the test results, the limits of permissible ash moisture depend on the required compaction factor, as presented in table 4.

Table 4. The relationship between the allowable coefficient of moisture and the coefficient of compaction of ash Reftinskaya state district power station.

Valid humidification coefficient K_w^a at the required compaction coefficient K_u			
K_u	0.98	0.95	0.90
K_w	0.70-1.40	0.60-1.50	Not limited

^aThe moisture coefficient of ash K_w is defined as the ratio of the actual moisture content of the material W to its optimum moisture content W_{opt} .

High dispersion, significant open porosity of the ash, microporosity of ash particles determine the high moisture capacity of this material. In terms of moisture capacity, ash exceeds not only natural sands, but also clay soils. The amount of water loss characterizes the amount of free (gravitational) water in the material, and is about 40%. A positive feature of ash as a road-building material is the ability to quickly give off "excess" water: from the total moisture capacity to the maximum molecular moisture capacity.

High dispersion of the ash determines a significant value of the height of the capillary rise of water in the layer of this material. In the compacted ash of the Reftinskaya state district power station, the capillary rise of water at a positive temperature was 1.2 m.

The main volume of ash located in the dumps of the Reftinskaya state district power station has a filtration coefficient of less than 0.1 m/day. and refers to a poorly permeable variety of soils according to GOST 25100 or to non-draining soils according to SP 34.13330.2012 [8].

The low density, high porosity of the mixture and the microporosity of the ash particles determine the effective thermophysical characteristics of the ash. The thermal conductivity coefficient λ of the ash in the air-dry state at a temperature of $t = 25^\circ\text{C}$ is 0.35-0.40 W/m·K. With increasing humidity of the ash to the value of the full molecular moisture capacity at 25°C , the thermal conductivity

coefficient increases to 0.50-0.55 W/m·K, and when freezing a sample with this humidity to 0.75-0.80 W/m·K.

The deformation properties of the ash are determined according to GOST 12248 by the compression method of samples with a broken structure, compacted to a density corresponding to a compaction coefficient of 0.95. Tests and calculations showed that the modulus of total ash deformation varies depending on the particle size distribution, density and moisture of the material from 4 to 14 MPa. The elastic modulus of ash varies from 20 to 70 MPa.

The strength properties of the ash are determined according to GOST 12248 by the method of a single-plane cut of samples with a broken structure at specified humidity and density values. Tests and calculations showed that the specific adhesion of the ash varies from 0.001 to 0.004 MPa, and the angle of internal friction from 35 to 40 degrees.

Thus, the results of studies of the construction properties of the ash of the Reftinskaya state district power station show that this material can be effectively used in various technologies of road construction: in the construction of the subgrade, the construction of base layers and coatings roads from ash-mineral mixtures, including in difficult transport and operational conditions of forest zones.

3.2. Development of technical solutions for the use of ash mixtures of Reftinskaya state district power station for the construction of high-strength coatings of forest roads

As laboratory test data show, favorable construction properties allow the use of Reftinskaya state district power station ash for the construction of high-strength layers of coatings for forest roads from an ash-mineral mixture: sand, ash and Portland cement, or some other mineral binder, such as lime. Moreover, according to the requirements of GOST 23558 [9], an ash-mineral mixture with a grade of strength not lower than M40 should be used.

The feasibility of using ash in the composition of the ash-mineral mixture is due to a reduction in the required amount of mineral binder while maintaining high physical and mechanical characteristics of the material [10]. According to the results of laboratory tests, sand from crushing screenings reinforced with 6% Portland cement with the addition of 4% ash allows the modulus of elasticity of the coating layer of the forest road to be achieved, similar to using sand reinforced with 10% Portland cement.

The selection of the composition of the ash-mineral mixture is carried out individually in each case. Layers of pavement coating from ash-mineral mixtures are allowed to arrange single-layer and two-layer. In this case, the minimum layer thickness is assigned at least 12 cm, the maximum - from the conditions for achieving the required density with available sealing means (usually 25-30 cm). The width of the foundation of the pavement design is assigned 0,5 m more than the width of the pavement in each direction (taking into account the width of the edge strips of the pavement). When calculating road structures, the thermal conductivity coefficient λ of ash-mineral materials should be taken equal to 1,4 W/m·K.

In the technical and economic comparison of pavement designs, it should be borne in mind that coatings or bases made from ash and mineral materials (especially those treated with lime) have reduced crack resistance, which allows to reduce the minimum allowable thickness of asphalt concrete coatings to 30% or to reduce the amount of work and maintenance costs for automobiles roads stipulated by regulatory requirements. In addition, layers of pavement treated with lime continue to gain strength for several years, which should also be taken into account when determining the minimum guaranteed service life of pavement [11].

Ash-mineral mixtures should be made and controlled in accordance with the requirements of GOST 23558 and taking into account the VSN 185 [12]. The strength of ash-mineral materials is determined according to GOST 10180 [13], taking into account refinements in GOST 23558 at the age of 90 days and is characterized by the brand. The relationship between the grade, compressive strength and tensile bending should comply with the requirements specified in table 5.

Table 5. Strength indicators of ash-mineral mixtures.

Strength grade	Strength, MPa (kgf / cm ²), not less	
	compression R_c	bending tensile R_b
M20	2.0 (20)	0.4 (4)
M40	4.0 (40)	0.8 (8)
M60	6.0 (60)	1.2 (12)
M75	7.5 (75)	1.5 (15)
M100	10.0 (100)	2.0 (20)

For operational control, it is allowed to determine the strength of the ash-mineral mixtures in the specified interim period. This period is set individually by the construction laboratory. At the same time, the strength in the interim should be at least 0.5 of the normalized value of strength at the age of 90 days.

Taking into account the average monthly air temperature of the coldest month, determined depending on the construction site of the forest road, ash-mineral mixtures are subdivided by frost resistance into grades F5 - F50 in accordance with GOST 23558. The required grade of frost resistance is assigned depending on the type of pavement according to table 6.

Table 6. Indices of frost resistance of ash-mineral mixtures.

Type of material	Type of pavement	Frost resistance mark for areas with average monthly air temperature of the coldest month, °C, not less than			
		from 0 to -5	from -5 to -15	from -15 to -30	below -30
Ash-material	Capital	F15	F25	F25	F50
	Lightweight	F10	F15	F25	F50
	Transition	F5	F10	F15	F25

Tests to determine the grade for frost resistance are carried out in accordance with GOST 10060.1 [14], taking into account the refinements in GOST 23558. For the brand for frost resistance, the established number of cycles of alternate freezing and thawing of samples is accepted, in which a compression strength of 90 days is allowed to be reduced by no more than 25 % of the rated strength at the same age.

The characteristics of the materials in the composition of the ash-mineral mixtures should be selected in accordance with the purpose of the ash-mineral mixture, the required grade for strength and frost resistance. If it is necessary to use materials with quality indicators below the listed requirements, a study should be carried out to confirm the feasibility and technical and economic feasibility of obtaining ash-mineral mixtures with standardized quality indicators.

Natural sand and from rock crushing screenings as part of ash-mineral mixtures must comply with the requirements of GOST 3344 [15] and GOST 8736 [16].

The following binders should be used to prepare the ash-mixture:

- Portland cement and slag Portland cement according to GOST 10178 [17], sulfate-resistant and pozzolanic cements according to GOST 22266 [18], as well as cements for building mortars according to GOST 25328 [19], grades no lower than 300.

- Building lime of I and II grades according to GOST 9179 [20].

To reduce the consumption of binders, increase strength, frost resistance and improve the technological properties of the ash-mineral mixture, chemical additives that meet the requirements of the relevant regulatory documents should be used [21].

Water for the manufacture of the ash-mineral mixture and the preparation of solutions of chemical additives must comply with the requirements of GOST 23732 [22]. The maximum permissible content of soluble salts should not exceed 10000 mg/l, incl. SO₄ - 2700 mg/l; Cl - 3500 mg/l.

The composition of the ash-mineral mixture is selected according to GOST 23558, taking into account the VSN 185. When selecting the composition, the required amount of binder is installed, which ensures the production of the ash-mineral mixture with a given brand in strength and frost resistance. Water consumption during the selection of the composition is determined on the basis of obtaining the maximum density of the mixture at optimal humidity.

On the basis of laboratory studies, the approximate content of binders for the preparation of ash-sand mixtures based on sand with the ash of the Reftinskaya state district power station for the construction of high-strength coatings of forest roads are given in table 7.

Table 7. Estimated content of binders for the ash mixture.

Strength grade	Estimated consumption of binder components, in% by weight of the mixture		
	Ash	Lime	Portland cement
20	10.5-13.5	4.2-5.4	-
	11-16	-	4.8-6
40	13.5-16.5	5.4-6.6	-
	15-19	-	6-7.2
60	16.5-19.5	6.6-7.8	-
	19-23	-	7.2-8.4
75	18-21	7.2-8.4	-
	23-24	-	8.4-9.6
100	20.5-23.5	9-10.2	-
	23-24	-	9.6-10.8

4. Conclusions

1. An analysis of the chemical composition of the ash at Reftinskaya state district power station indicates that this material is acidic and has a very low potential for the manifestation of hydraulic properties. The phase-mineralogical composition indicates that ash is represented by stable compounds and minerals that are not susceptible to various types of decomposition under the influence of weather and climate factors and mechanical stresses. Ash is not aggressive to building structures based on cement, bitumen, etc. To metal structures, ash is moderately aggressive.

2. The research results show that the ash of the Reftinskaya state district power station does not have clearly expressed optimal humidity and maximum skeleton density. A positive feature of ash as a road-building material is the ability to quickly give off "excess" water: from the total moisture capacity to the maximum molecular moisture capacity. In the compacted ash of the Reftinskaya state district power station, the capillary rise of water at a positive temperature was 1.2 m. The filtration coefficient of the ash was less than 0.1 m/day. Therefore, the ash is a poorly permeable variety of soil or non-draining soil.

3. The low density, high porosity of the mixture and the microporosity of the ash particles determine the effective thermophysical characteristics of the ash. The thermal conductivity coefficient λ of the ash in the air-dry state at a temperature of $t = 25^\circ\text{C}$ is 0.35-0.40 W/m·K. The modulus of the total ash deformation varies depending on the particle size distribution, density and moisture of the material from 4 to 14 MPa. The specific adhesion of the ash varies from 0.001 to 0.004 MPa, and the angle of internal friction from 35 to 40 degrees.

4. The results of studies of the construction properties of ash show that this material can be effectively used in various technologies of road construction, including in difficult transport and operating conditions of the forest zone for the construction of high-strength layers of coatings of forest roads from the ash-mineral mixture: sand, ash and Portland cement, or another mineral binder, such as lime.

5. The expediency of using ash in the composition of the ash-mineral mixture is due to the reduction in the required amount of mineral binder while maintaining high physical and mechanical characteristics of the material. According to the results of laboratory tests, sand from crushing screenings reinforced with 6% Portland cement with the addition of 4% ash allows the modulus of elasticity of the coating layer of the forest road to be achieved, similar to using sand reinforced with 10% Portland cement.

6. Coatings or bases of pavements made of ash and mineral materials (especially those treated with lime) have reduced crack resistance, which allows to reduce the minimum allowable thickness of asphalt concrete coatings to 30% or to reduce the amount of work and maintenance costs for roads provided for by regulatory requirements. In addition, the layers of pavement treated with lime continue to gain strength for several years.

7. The characteristics of the materials in the composition of the ash-mineral mixtures should be selected in accordance with the purpose of the ash-mineral mixture, the required grade for strength and frost resistance. To reduce the consumption of binders, increase strength, frost resistance and improve the technological properties of the ash-mineral mixture, chemical additives should be used. Water consumption during the selection of the composition is determined on the basis of obtaining the maximum density of the mixture at optimal humidity. Based on the laboratory studies, approximate compositions of binders for the preparation of ash-sand mixtures based on sand with ash of the Reftinskaya state district power station for the construction of high-strength coatings of forest roads have been obtained.

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